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Breaking Waves and Microwave Polarimetric Emissivities: Final Report

William E. Asher

Applied Physics Laboratory, University of Washington

1013 NE 40th Street

Seattle, WA 98105

phone: (206) 543-5942

facsimile: (206) 543-6785

e-mail: asher@apl.washington.edu

Award Number: N00014-00-1-0152

<http://www.apl.washington.edu>

OBJECTIVES

Our long-term goals were to provide polarimetric microwave emissivities of seawater that could be used to test models for predicting the microwave electromagnetic response of the ocean surface and to understand the physical processes that cause the changes in microwave emissivity observed for breaking waves. In order to achieve these objectives we conducted several field experiments designed to provide a detailed look at the physical processes affecting the microwave radiometric signal from breaking waves and foam patches.

APPROACH

Recent data have indicated that wind speed and direction can be measured using passive microwave radiometers [Piepmeier and Gasiewski, 2001; Wentz, 1992; Wick *et al.*, 2000; Yueh *et al.*, 1999; Yueh *et al.*, 1997; Yueh *et al.*, 1995] and the WindSat passive polarimetric satellite instrument is currently operating to provide the initial proof-of-concept satellite data. Multi-frequency radiometers are an attractive method for satellite-based wind measurements because they also provide estimates of sea surface temperature, sea-ice coverage, rain rate, water vapor concentration, and cloud water content. For this reason, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) has chosen to use passive polarimetric radiometry to fulfill the ocean surface wind vector environmental data record. This puts particular emphasis on ensuring wind vector retrieval algorithms used by the Conical Microwave Imager/Sounder (CMIS) currently under design by NPOESS accurately model the physical processes affecting the sea surface microwave brightness temperatures.

Because the radiometric signals needed for retrieving the wind direction are only a few degrees Kelvin at most, accurate retrieval of vector wind fields from microwave radiometric data requires understanding how microwave emissivity is determined by ocean surface properties. It is also critical to understand how this emissivity varies as a function of azimuthal look angle of the radiometer with respect to the wind vector. Although it is known that the ocean surface emissivity is primarily a function of the surface roughness and the fractional area coverage of breaking waves and foam, the dependence of the emissivity of foam on both incidence angle and azimuthal angle have not been characterized.

In collaboration with Dr. L. A. Rose from the Naval Research Laboratory in Washington D.C. and Prof. S. Reising from the University of Massachusetts, we have conducted a series of field experiments that have provided a more thorough understanding of the relationship between foam, breaking waves, surface roughness, and microwave emissivity. The first of these experiments was conducted in May 2000 on the Chesapeake Bay using a specially designed foam generator. This device

generated a uniform, stable patch of foam on the water surface. A crane was used to position an X-band (10.8 GHz) and a Ka-band (36.5 GHz) radiometer over the foam raft so that the emissivity of beam-filling foam could be measured as a function of radiometer incidence angle. The data show that for all polarizations and incidence angles measured, the foam emissivity is significantly less than one, which implies that ocean surface foam should not be modeled as a blackbody with an emissivity of one [Rose *et al.*, 2002].

In September 2000, radiometric, foam coverage, and air-sea interaction data were collected from the R/P FLIP during the Fluxes, Air-Sea Interaction and Remote Sensing (FAIRS) experiment for wind speeds of up to 15 m/s with concomitant large-scale breaking waves. The data from this experiment suggested that the emissivity of a whitecap is not constant over its lifetime. Furthermore, the data also suggest that the decaying foam patch left in the wake has a higher emissivity than the actively breaking crest and that there are subtle differences in the emissivity of the breaking wave as a function of azimuthal angle. However, the intermittent and spatially sparse nature of oceanic breaking waves make it difficult to acquire repeated measurements of beam-filling foam.

The third field experiment was the Polarimetric Emissivity of Whitecaps Experiment (POEWEX) conducted in October 2002 at the OHMSETT wave basin in Leonardo, New Jersey. OHMSETT is a 200-m long by 20-m wide wave basin filled with seawater. A removable shoal was built and installed in OHMSETT to generate reproducible breaking waves at a fixed location in the wave basin. Three fully polarimetric microwave radiometers were used, a 10.8 GHz unit from the Naval Research Laboratory, and two radiometers from the University of Massachusetts, one at 19 GHz and one at 36.5 GHz.

SIGNIFICANT RESULTS

1. Showed that the microwave emissivity of a foam-covered water surface does not behave as a blackbody in the microwave region [Rose *et al.*, 2002].
2. Demonstrated that when imaging bubbles in energetic flows such as the wakes of breaking waves, camera shutter speeds must be set to at least 1/10,000 s in order to image fast-moving bubbles [Asher *et al.*, 2005].
3. Provided further evidence that fractional area whitecap coverage can be estimated from microwave brightness temperature [Aziz *et al.*, 2005].
4. Provided new data on the relationship between sea surface microwave emissivity and wind stress, atmospheric stability, and sea surface wave properties [Aziz *et al.*, 2005].
5. Showed that the fractional area foam coverage of a breaking wave, and the change in overall scene microwave brightness temperature it induces, depends on the azimuthal look angle (as measured with respect to the direction of wave propagation) [Padmanabhan *et al.*, 2004].

IMPACT/IMPLICATION

POEWEX provides the first detailed study of the polarimetric microwave emissivities of breaking waves. As such, the data will be valuable for developing parameterizations of the emissivities of oceanic breaking waves, and in designing future experiments for calibrating and validating the

performance of the WindSat microwave polarimeter. Data from POEWEX will also be useful in designing and evaluating the errors in retrieval algorithms for CMIS.

REFERENCES

- Asher, W.E., T.M. Litchendorf, and K. Phadnis, The effect of shutter speed on measuring size-segregated bubble concentrations in energetic flows, *J. Atm. Ocean. Tech.*, to be submitted, 2005.
- Aziz, M.A., S.C. Reising, W.E. Asher, L.A. Rose, P.W. Gaiser, and K.A. Horgan, Effects of Air-Sea Interaction Parameters on Ocean Surface Microwave Emission at 10 and 37 GHz, *IEEE Trans. Geosci. Rem. Sensing*, in press, 2005.
- Padmanabhan, S., S.C. Reising, W.E. Asher, L.A. Rose, and P.W. Gaiser, Parameterization of Microwave Emission due to Foam to Improve the Accuracy of Satellite-Based Retrieval Algorithms, in *International Geoscience and Remote Sensing Symposium*, IEEE, Anchorage, Alaska, 2004.
- Piepmeyer, J.R., and A.J. Gasiewski, High-resolution passive polarimetric microwave mapping of ocean surface wind vector fields, *IEEE Trans. Geosci. Rem. Sensing*, 39, 606-622, 2001.
- Rose, L.A., W.E. Asher, S.C. Reising, P.W. Gaiser, K.M. St. Germain, D.J. Dowgiallo, K.A. Horgan, G. Farquharson, and E.J. Knapp, Radiometric measurements of the microwave emissivity of foam, *IEEE Trans. Geosci. Rem. Sensing*, 40, 2619-2625, 2002.
- Wentz, F.J., Measurement of oceanic wind vector using satellite microwave radiometers, *IEEE Trans. Geosci. Rem. Sensing*, 30, 960-972, 1992.
- Wick, G.A., J.J. Bates, and C.C. Gottschall, Observational evidence of a wind direction signal in SSM/I passive microwave data, *IEEE Trans. Geosci. Rem. Sensing*, 38, 823-837, 2000.
- Yueh, S.H., W.J. Wilson, S.J. Dinardo, and F.K. Li, Polarimetric microwave brightness signatures of ocean wind directions, *IEEE Trans. Geosci. Rem. Sensing*, 37 (2), 949-959, 1999.
- Yueh, S.H., W.J. Wilson, F.K. Li, S.V. Nghiem, and W.B. Ricketts, Polarimetric brightness temperatures of sea surfaces measured with aircraft K- and Ka-band radiometers, *IEEE Trans. Geosci. Rem. Sensing*, 35, 1177-1187, 1997.
- Yueh, S.H., W.J. Wilson, F.K. Li, W.B. Ricketts, and S.V. Nghiem, Polarimetric measurements of sea surface brightness temperatures using an aircraft K-band radiometer, *IEEE Trans. Geosci. Rem. Sensing*, 33, 85-92, 1995.

PEER-REVIEWED PUBLICATIONS

Asher, W.E., T.M. Litchendorf and K. Phadnis. "The Effect of Shutter Speed on Measuring Size-Segregated Bubble Concentrations in Energetic Flows," to be submitted, *J. Atm. Oceanic Tech.*

Aziz, M.A., S.C. Reising, S. Padmanabhan, W.E. Asher, L.A. Rose, P.W. Gaiser and K.A. Horgan, 2004. "Effects of Air-Sea Interaction Parameters on Ocean Surface Microwave Emission at 10 and 37 GHz," *IEEE Trans. Geosci. Rem. Sens.*, in press.

Chen, D., L. Tsang, L. Zhou, S.C. Reising, W.E. Asher, L.A. Rose, K.H. Ding, and C.-T. Chen, 2003. "Microwave Emission and Scattering of Foam based on Monte Carlo Simulations of Dense Media," *IEEE Trans. Geosci. Rem. Sens.*, **41**, 782-790.

Rose, L.A., W.E. Asher, S.C. Reising, P.W. Gaiser, K.M. St. Germain, D.J. Dowgiallo, K.A. Horgan, G. Farquharson, and E.J. Knapp, 2002. "Radiometric measurements of the microwave emissivity of foam," *IEEE Trans. Geosci. Rem. Sens.*, **40**, 2619-2625

Guo, J., L. Tsang, W.E. Asher, K.-H. Ding, and C.-T. Chen, 2001. "Applications of Dense Media Radiative Transfer Theory for Passive Microwave Remote Sensing of Foam Covered Ocean" *IEEE Trans. Geosci. Rem. Sens.*, **39**, 1019-1027.

CONFERENCE PRESENTATIONS

Padmanabhan, S., S.C. Reising, W.E. Asher, L.A. Rose and P.W. Gaiser, 2004. "Parameterization of Microwave Emission due to Foam to Improve the Accuracy of Satellite-Based Retrieval Algorithms," *in press, Proc. Int. Geosci. Remote Sensing Symp.*, Anchorage, Alaska, September, 2004.

Asher, W.E., T.M. Litchendorf and K. Phadnis, 2004. "The Effect of Shutter Speed on Measuring Size-Segregated Bubble Concentrations in Energetic Flows," 2004 SOLAS General Science Meeting, Halifax, Nova Scotia, October, 2004.

Reising, S.C., S. Padmanabhan, M.A. Aziz, W.E. Asher, L.A. Rose, and P.W. Gaiser, "Microwave Emission of Reproducible Breaking Waves: The POLarimetric Emissivity of Whitecaps Experiment (POEWEX '02)," *IEEE International Geoscience and Remote Sensing Symposium*, Toulouse, France, July 2003.

Padmanabhan, S., and S.C. Reising, "Radiometric Measurements of the Microwave Emissivity of Reproducible Breaking Waves," *IEEE International Geoscience and Remote Sensing Symposium*, Toulouse, France, July 2003.

Reising, S.C., S. Padmanabhan, M.A. Aziz, W.E. Asher, L.A. Rose, and P.W. Gaiser, "Microwave Emission of Reproducible Breaking Waves The POLarimetric Emissivity of Whitecaps Experiment (POEWEX '02)," *USNC/CNC/URSI North American Radio Science Meeting*, Columbus, Ohio, June 2003.

Reising, S.C., J. Pons, S. Padmanabhan, W.E. Asher, N. Duffo, and A. Camps, "Passive polarimetric

remote sensing of the sea surface during REDComparison of microwave radiometric signatures with air-sea interaction measurements," *12th Conference on Interactions of the Sea and Atmosphere, American Meteorological Society Annual Meeting*, Long Beach, California, February 2003.

Reising, S.C., W.E. Asher, L.A. Rose, and M.A. Aziz, "Passive polarimetric remote sensing of the ocean surface: The effects of surface roughness and whitecaps," *Proceedings of the 27th General Assembly of the International Union of Radio Science (URSI)*, Maastricht, Netherlands, August 2002.

Asher, W.E., S.C. Reising, and L.A. Rose, "The effect of surface roughness and whitecaps on sea surface microwave emissivity," *Progress in Electromagnetics Research Symposium*, Cambridge, Massachusetts, July 2002.

Reising, S.C., K.A. Horgan, M.A. Aziz, W.E. Asher, and L.A. Rose, "The effects of surface roughness and whitecaps on sea surface microwave emissivity," *IEEE International Geoscience and Remote Sensing Symposium*, Toronto, Canada, June 2002.

Reising, S.C., K.A. Horgan, and E.J. Knapp, W.E. Asher, L.A. Rose, K.M. St. Germain, P.W. Gaiser, and D.J. Dowgiallo, "Passive polarimetric measurements of the effects of foam and roughness on microwave emissivity," Paper F4-5, *2002 National Radio Science Meeting*, Boulder, Colorado, January 2002.

Reising, S.C., W.E. Asher, L.A. Rose, P.W. Gaiser, K.M. St. Germain, D.J. Dowgiallo, K.A. Horgan, and E.J. Knapp, "Passive polarimetric measurements of the effects of foam and roughness on microwave emissivity," *Specialist Meeting on Microwave Remote Sensing*, Boulder, Colorado, November 2001.

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